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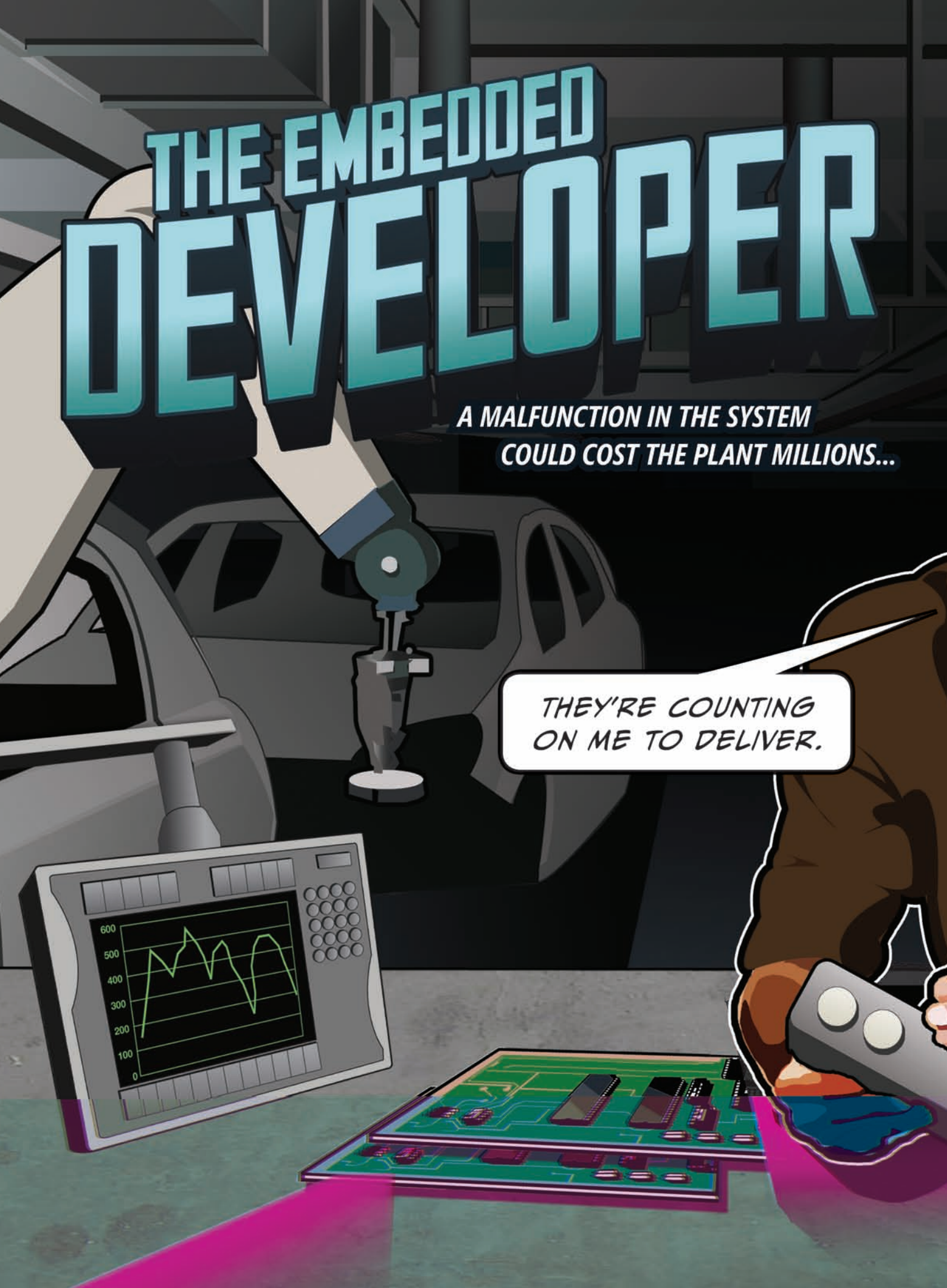
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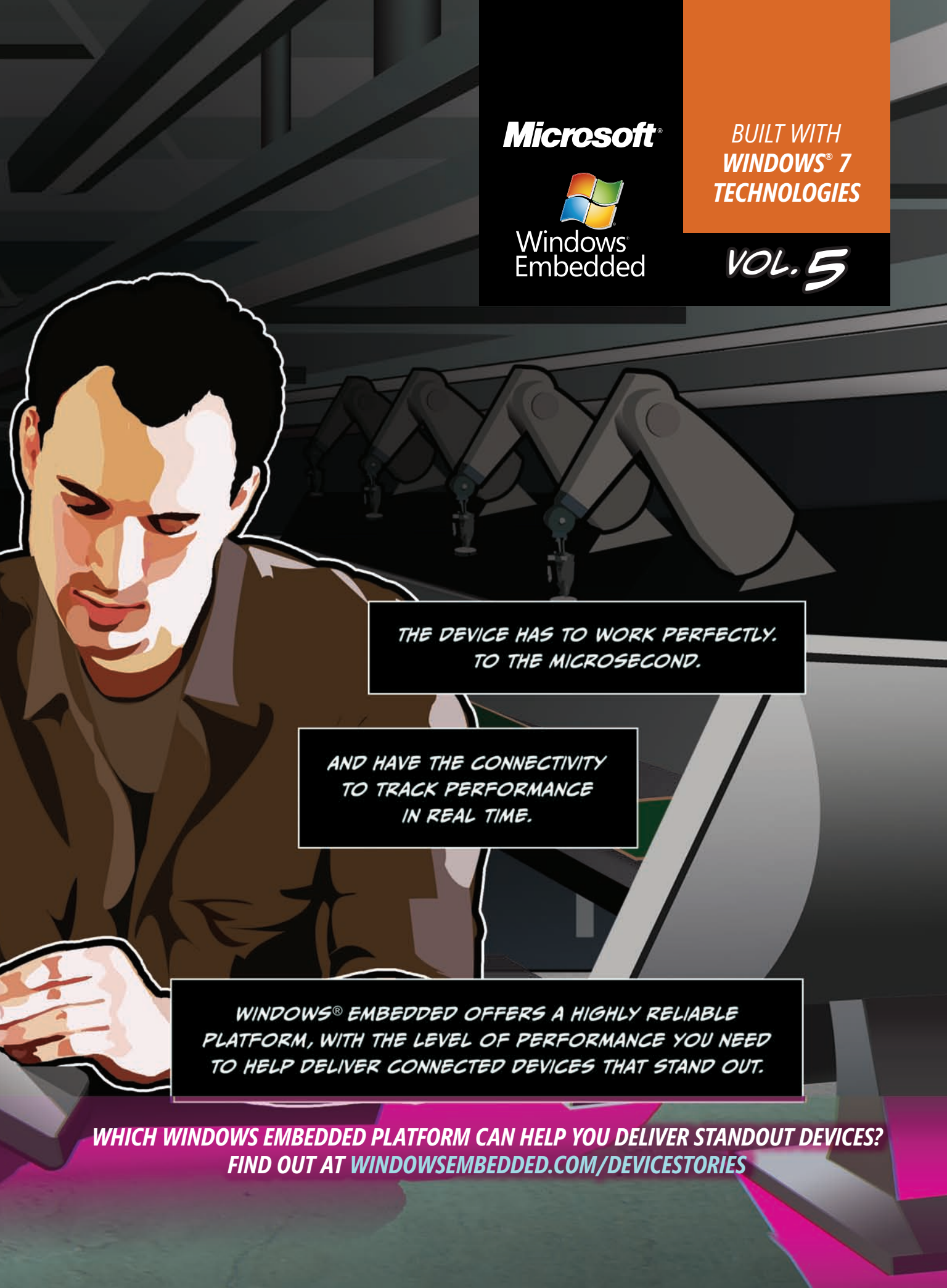
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On the cover

The Parrot AR.Drone "quadricopter" turned heads during its debut at the 2010 Consumer Electronics Show (CES) in Las Vegas. With Wi-Fi-enabled control via an iPhone and two onboard cameras, the drone was just one of many gadgets at CES that showcased embedded technologies, demonstrating how embedded is now driving consumer electronic designs. Photo courtesy of CES, www.cesweb.org.

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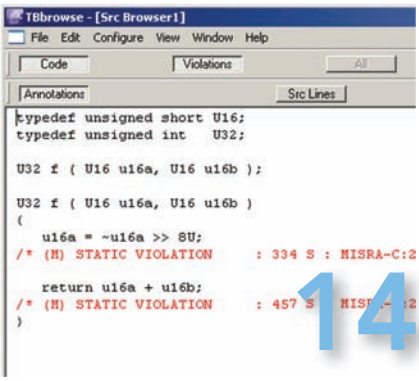

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Left to My Own Devices

Don Dingee

Out of the shadows

In previous years, people asked why, as an embedded magazine, we would go to the Consumer Electronics Show (CES). It seemed for the longest time that the show was all about PCs, Microsoft, TVs, cameras, and home audio stuff. But we started seeing a shift to smartphones, set-top boxes, and connected devices of all kinds a couple years ago, and that's now accelerating very quickly.

This year, I didn't see much of the show, but I was there the whole time. What I did see is quite interesting and told me that the embedded industry has hit the big time.

Instead of being scattered all over Las Vegas in various hotel suites in the "shadows," the CES organizers created a much more critical mass of briefing rooms – "the meeting place" – in the South Hall. With a few exceptions, I did not leave that area, because almost everyone I needed to talk to was there.

I was briefed by Xilinx on their consumer electronics strategy and how FPGAs with cores and logic are hitting both price and performance points for customers. Atmel told me about their touch-screen controllers, mentioning that these are used in the Motorola Droid. MIPS Technologies and ARM both had a whole set of ideas for the digital home. Applied Micro showed off not only processor silicon, but also a vision for use in things like an appliance that pairs to a smartphone via Bluetooth and an app, automatically moving pictures shot with the phone and uploading them to the social net of choice.

Around the core, Atheros showed off a wide range of 802.11n, power-line, and GPS connectivity. QuickLogic revealed their plans for increasing mobile display quality. Imagination Technologies had those, too, plus some new ideas for better connectivity and even multicore processing.

There were rows and rows of companies I didn't get to visit, but the message was clear: Embedded is driving consumer electronic designs now, so I'm renaming CES the "Consumer Embedded Show" and considering how devices are being used in new ways.

It's not that far of a stretch when you look out on the show floor. For example, take our cover photo of the Parrot AR.Drone. It's a helicopter ("quadricopter") controlled via an Apple iPhone app over Wi-Fi that can be flown around just for fun or used inside an augmented reality video game.

Or consider the INRIX TRAFFIC! solution, which is much more than just an app, as it is backed by tons of real-time traffic data and predictive modeling of things like "street waves" that show the flow of vehicles in an area.

Or think about a device such as Pocket Radar, which puts a radar gun in the hands of sports enthusiasts and neighborhood watchers in an inexpensive, easy-to-use form. Or something like the Robonica robot with ZigBee and RFID inside to enable interactive gaming with the player controlling the robot.

Embedded designers are powering up exciting new things that do more than just communicate; they engage and involve the consumer in a new experience. The old ways are done, and the new days for embedded are here.

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Optimizing microcontroller power efficiency for ultra-low-power designs

By Jukka Eskelinen and Kim Meyer

Ultra-low-power applications require power optimization at all levels, from the microcontroller architecture up through the application layer. Optimal platforms for developing efficient, single-cell-powered architectures can enable designers to build compact battery-operated devices at the lowest cost and highest power efficiency.

Designers typically optimize device power consumption by reducing active processing time and increasing how long microcontrollers (MCUs) can reside in sleep mode. With the rise of ultra-low-power applications, however, this approach no longer suffices.

For devices such as electric toothbrushes, personal media players, remote controllers, wireless sensors, and a wide range of other portable and handheld devices, power management needs to be implemented at all levels of a system. By optimizing power consumption through efficient single-cell voltage conversion, utilizing multiple current modes, introducing smart battery management, and implementing power-saving techniques at the application level, power consumption can be coordinated across an entire system.

Efficient voltage conversion

Many ultra-low-power applications are moving to single battery cell architecture to decrease device cost, size, and weight. Reducing the power supply to a single cell is an attractive option because it simplifies battery holder mechanics and results in significantly smaller and lighter products.

While the voltage from a single battery cell usually ranges from 1.2 V to 1.5 V when fully charged, cells can drop below 1 V while still possessing a substantial amount of usable energy. Driving motors, LEDs, and even the microcontroller itself from a single cell requires a regulator to boost the available voltage to appropriate levels.

The ATtiny43U has an integrated regulator that can boost voltages as low as 0.7 V (see Figure 1), allowing discharging to continue closer to the end of a cell's reserves. This integrated regulator offers a 1 microamp (typical) idle current, automatic start as soon as sufficient voltage is available, and support for any battery technology, enabling developers to use 1.6 V alkaline or silver oxide, 1.5 V Li-ion, 1.4 V zinc-air, and 1.2 V NiMH and NiCd, among others.

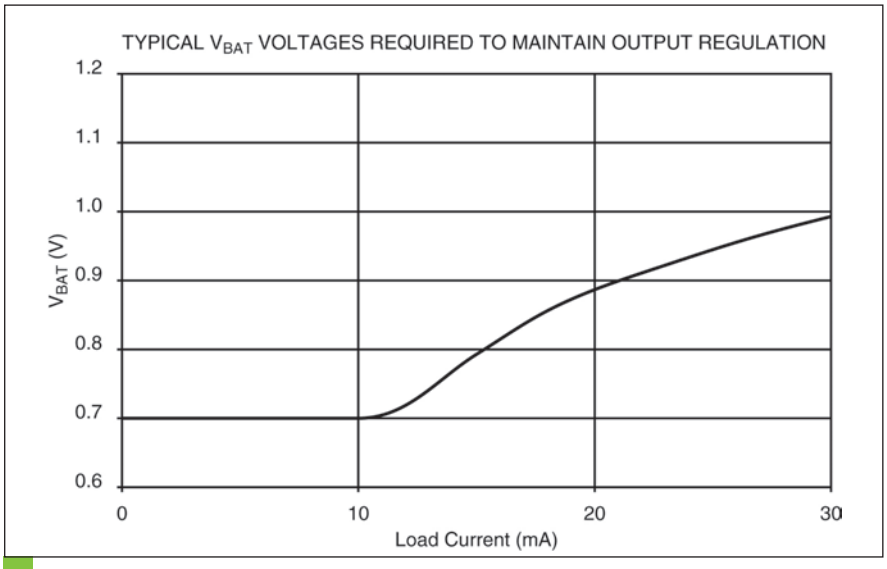

Figure 1 | The ATtiny43U operates at voltages down to 0.7 V.

Boost and low current modes

High current capacity without external drive circuitry is also important for many applications. The ATtiny43U's boost regulator can drive up to 30 mA, enabling direct control of high-brightness LEDs and small motors. Figure 2 shows the ATtiny43U's conversion efficiency for particular load currents based on remaining charge.

As seen in Figure 2, high current operation is less efficient than when running at a lower current, but most high current applications do not need to operate in high current mode continuously. If the architecture is locked into a high current mode, then these devices will operate at reduced efficiency even when the device only requires a low current draw.

To preserve efficiency, the MCU must be able to support multiple operating modes. When the device requires high current and tightly regulated Vcc, the MCU and regulator will operate in a regulated mode. When motors or other peripherals are not in use, and the load current drops down below 0.6 mA, the regulator automatically switches into a low current mode, performing more efficient power conversion.

Additionally, at light or no loads the converter in regulated mode will periodically reach its duty cycle low limit. By automatically dropping into low current mode, the converter stops switching and reduces current consumption to a minimum while still remaining active (see Figure 3).

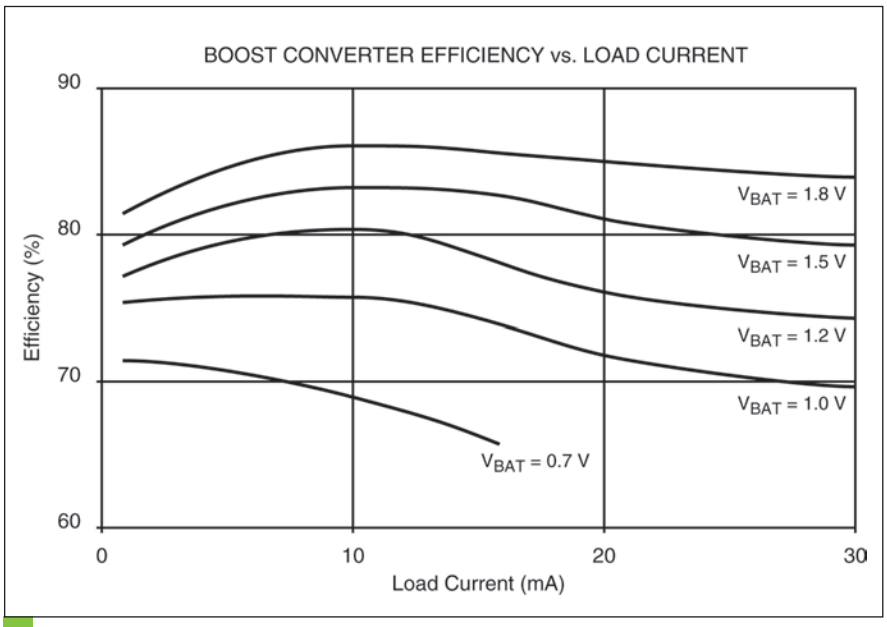

Figure 2 | Boost efficiency for load currents depends on input voltage.

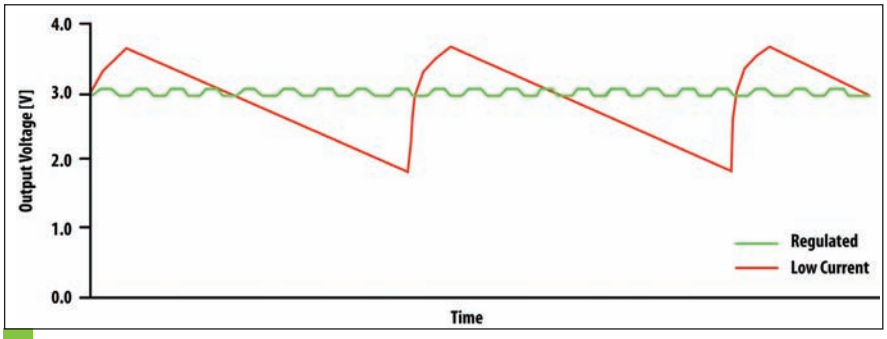

Figure 3 | The converter periodically reaches its duty cycle low limit in regulated mode and cuts current consumption in low current mode.

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In the main mode of operation, active regulated mode, output voltage remains stable within 3 V ±100 mV. Also note that the typical transition voltage changes as the energy in the cell is depleted (see Figure 4).

Smart battery management

Rechargeable batteries require careful monitoring and charging control within set limits to ensure safe usage and optimum operating life. Different battery chemistries have different voltage thresholds to which they can be safely charged and discharged.

The ATtiny43U's firmware can monitor the battery voltage using the built-in Analog-to-Digital Converter (ADC) and decide when to put itself in stop mode, thus thoroughly draining disposable batteries while ensuring the maximum life of rechargeable cells over multiple recharging cycles.

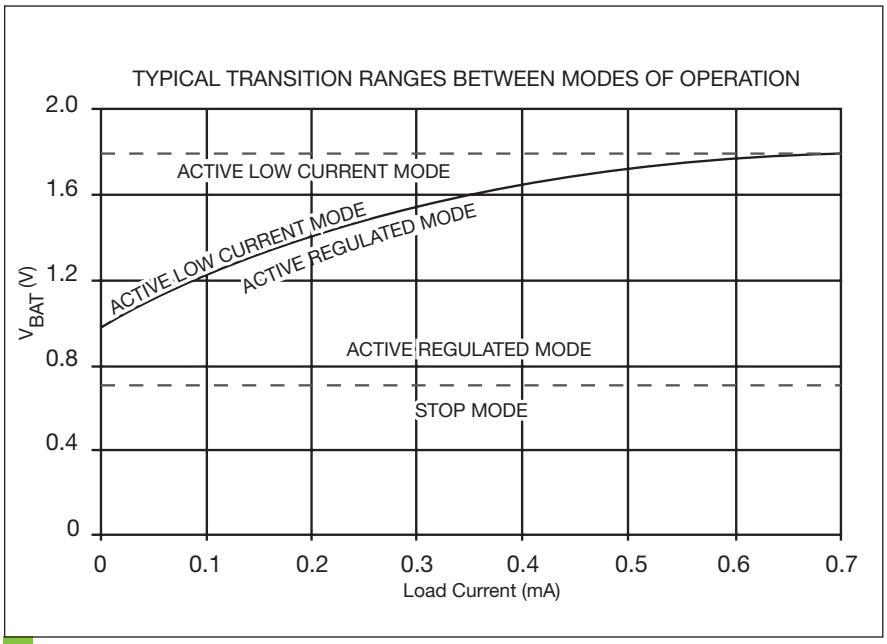

Figure 4 | Transition levels between modes of operation change as energy in a cell is depleted.

Mode of operation	Condition	Level of activity	Can wake device	Current consumption
Power down	V_{BAT} = 1.2 V	No clocks running; retains RAM	External interrupt, pin change, or watchdog timer	5 µA
Idle	V_{BAT} = 1.2 V	All peripherals run as normal; no code can run	Any peripheral can wake up CPU	0.7 mA
Active	V_{BAT} = 1.2 V f_{CLK} = 4 MHz	Fully active	Already awake	5 mA

Table 1 | Typical modes of operation offer developers different current consumption options.

While automatically shutting down an MCU protects rechargeable cells, an abrupt loss of power may not be acceptable from an application perspective. For example, shutting a camera down suddenly will leave the lens exposed and vulnerable. Using the ADC to measure the battery voltage at regular time intervals gives the application a chance to place devices into a safe configuration before shutdown.

More power-saving techniques

Many applications add an MCU as a secondary processor to assist the main application processor, offloading tasks such as updating a display, monitoring a keyboard, operating small motors, and intelligently managing smart batteries. Using an MCU this way enables the application processor to sleep longer uninterrupted, resulting in substantial power savings.

Ultra-low-power MCUs also require multiple sleep modes. For example, a sensor application may monitor temperature until it exceeds a threshold. Keeping the entire MCU in active mode during monitoring consumes more power than is actually necessary. Support for different sleep modes that allow developers to shut down different parts of the device enable better power conservation (see Table 1).

Many other innovations in the ATtiny43U architecture increase power efficiency in both active and sleep modes:

Low-power brownout detection

While zero-power brownout detectors consume no power, they are also slow to respond and can require a full millisecond to detect a below-threshold voltage, thus leaving the MCU at risk. Alternatively, a sleeping brownout detector can identify brownout conditions in 2 microseconds while drawing only 20 microamps.

Digital input disable registers

Multiplexing inputs to a peripheral such as an ADC helps low-pin-count devices, but when voltages in the range of Vcc/2 are applied, the transistors comprising the input buffer will experience current leakage. The use of dedicated input disable registers with one disable bit per analog input enables developers to disable individual input buffers to prevent leakage.

Power reduction register

While multiple sleep modes simplify power management, they often turn whole blocks of peripherals on or off. A power reduction register gives developers full control to turn off individual peripheral modules. Disabling one peripheral module can result in a reduction of 5-10 percent of the total power consumption in active mode and 10-20 percent in idle mode.

Flash sampling

Traditional flash is designed to always be enabled while in active mode. At lower clock speeds, however, the flash read time will be less than the clock period. Flash sampling enables the flash on the order of 10 ns to sample the array's contents and then immediately disables it, reducing average power consumption.

Seeing the difference

Development kits provide an effective means for testing an MCU's efficiency under real-world operating conditions. The ATtinyx3U top module attaches to the ATSTK600 development board (see Figure 5). Using this kit, developers can test the limits of single-cell operation, profile power consumption while directly driving a high-brightness LED, and drive the integrated boost regulator's auto shutdown and power-on features to tune power thresholds to utilize the maximum capacity of cells within safe parameters.

MCUs integrating an on-chip regulator with configurable modes efficiently bridge the gap between the minimum supply voltage of the MCU and typical output voltages of standard single-cell battery technologies, enabling developers to minimize power consumption based on available load conditions and battery voltage. With only one battery, no external regulator, the ability to drain cells down to 0.7 V, and high current capacity for LEDs and small motors, designers can build compact, cost-effective, battery-operated devices that are truly ultra-low-power. ECD

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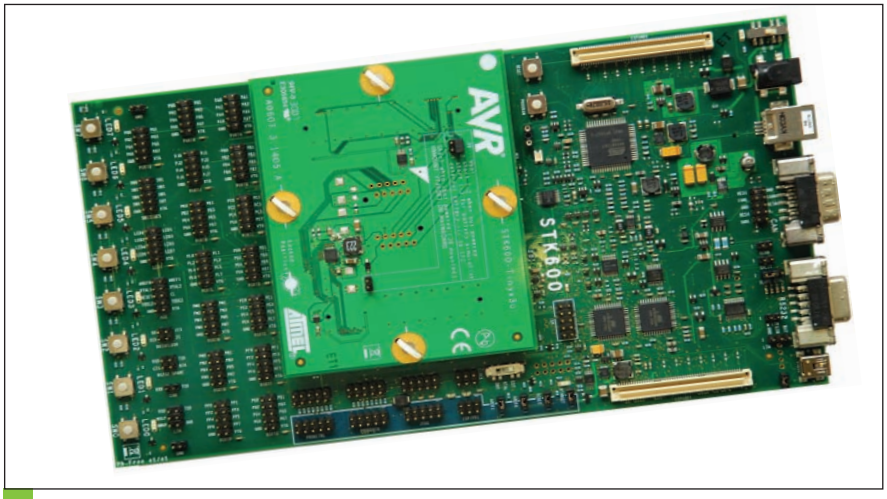

Figure 5 | The ATSTK600 development board with the ATtinyx3U top module attached allows developers to test MCU efficiency.

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Static analysis aids code portability

By Chris Tapp

Portability is a tricky issue related to nuances in underlying architecture support, compilers, and coding standards. Static analysis tools can speed up the process of spotting and correcting portability issues, as shown in the following examples.

Code reuse is often a major consideration within new projects, both in terms of making use of legacy code from preceding projects and as a foundation for those that will follow. Static analysis can be used to ensure that legacy code does not become a source of issues within a project and to guarantee that any code produced during its development will not afflict any projects that draw on it as a code base.

C code is particularly vulnerable to porting issues, especially since compilers cannot be expected to detect them as code will comply with the language specification (assuming no language extensions are used). It is therefore essential that developers use static analysis tools to confirm that porting will proceed as planned. Static analysis tools can help with this in several ways.

Portability issues arising from the size of int

The precision (number of bits) in an int can differ between systems. To deal with this, it is common to define a set of typedefs to map system types onto application types. The following example can be defined for a 16-bit architecture:

```
typedef unsigned char U8;
typedef unsigned int  U16;
typedef unsigned long U32;
```

This example could then be changed to the following if the code were ported to a 32-bit architecture:

```
typedef unsigned char  U8;
typedef unsigned short U16;
typedef unsigned int   U32;
```

However, porting is not that simple, as changes in the size of int can have some less obvious effects on the code. For example, any expression whose result depends on the effects of integer promotion may exhibit different behavior. Because of this, such a change is only appropriate if the precision within all expressions containing objects of the affected types fits the purpose. Static analysis can be used to validate this assumption.

Compilers will not report any of these issues because the code is perfectly valid for the targeted environment, even though it might not behave as expected.

Portability issues arising from compiler implementation

Differences in the implementation-defined, unspecified, or undefined behavior associated with the compiler can lead to defects when porting.

Implementation-defined behavior is behavior that might differ between compilers but is documented by the compiler vendor. Static analysis tools can detect code that invokes such behavior so that it can be eliminated to facilitate porting.

Unspecified or undefined behavior can also be detected; however, it presents more than just a portability issue, as such behavior can change in an undocumented way between different versions of the same compiler and might even change between various use cases within the same compiler. Code invoking such behavior could work but most likely would be very fragile. Notably, moving to a different version of a compiler can be considered as porting.

Compilers are not required to detect uses of implementation-defined, unspecified, or undefined behavior because the code is perfectly valid.

Coding standards

Publicly available coding standards like MISRA C:2004 (www.misra-c.com), which can be rigorously enforced by static analysis tools, include rules that defend against these portability issues. The subsequent examples make use of this standard.

Integer conversions within C

The rules governing how and when different arithmetic types are implicitly converted during the evaluation of an expression within C are complex. To ensure that results are as expected when code is ported, all operations within an expression should be conducted in the same type after all such implicit conversions have been taken into consideration.

The implicit conversions associated with integer promotion can easily lead to code performing in a way that is significantly different from what developers expect. Integer promotion basically requires that any type smaller than an int (such as char, short) be converted to an int before it is used as an operand within an expression. Many embedded systems make extensive use of these types because they often allow for more efficient usage of memory resources, which could be restricted to save cost, space, and power.

Integer promotion is value-preserving (meaning the magnitude and sign are preserved), but the signedness of an object might change. Additionally, the expression will be evaluated in a type that is wider than the type of the operands. Consider the following example:

```
U8 u8a = 200U;
U8 u8b = 100U;
U8 u8r = u8a + u8b;
```

In this example, u8a and u8b are both converted to signed int with a width of at least 16 bits before the addition takes place. The result of the addition is then implicitly converted back to 8 bits before it is stored in u8r. In this case, developers are likely to expect the result (44), as it is reasonable to assume they are aware of the modulo 2 arithmetic that takes place on assignment. This means that the result is effectively the same as it would have been if the operation had taken place with 8-bit precision (integer promotion did not affect the result).

However, when integer promotion occurs at the same time as an implicit widening conversion, there is potential for confusion. Consider the following:

```
U16 u16a = 0xffffU;
U16 u16b = 0x0001U;
U32 u32r = u16a + u16b;
```

On a 32-bit architecture, u32r will have type unsigned int while u16a and u16b will have type unsigned short. Integer promotion will cause the operands to be converted to signed int before the addition takes place, and the result will be implicitly converted to unsigned int on assignment, giving a final value of 0x10000. Developers can (perhaps justifiably) rely on the integer promotion taking place to ensure that the addition does not wrap as it would if 16-bit arithmetic were used.

If developers decide to port the code to a 16-bit architecture, u32r will then have type unsigned long and u16a and u16b will have type unsigned int. This time, no conversions will be applied to the operands, which are already unsigned int, before the addition takes place (also in unsigned int), and the result of 0x0000 will be implicitly converted to unsigned long on assignment, giving a final value of 0x0000. The assumption that the addition would be performed in a wider type is now no longer valid, and there is a risk that an unintended wraparound has occurred.

This shows how easily code can exhibit different behavior when it is ported from one platform to another. The real issue here relates to the implicit widening conversion that takes place on assignment of the result. This can be eliminated by ensuring that the expression is always evaluated with the necessary precision using a cast, for example:

```
u32r = ( u32 ) u16a + u16b;
```

The (u32) cast ensures that the expression is always evaluated in a type with the appropriate precision. In the previous example, this means the expression is evaluated in unsigned long rather than unsigned int. As shown in Figure 1, static analysis can easily detect implicit widening.

Integer promotion can also affect other operations. Consider the following:

```
u16a = 0x1234U;
u16r = ~u16a >> 8;
```

On a 16-bit architecture, this will lead to the bits of u16a being inverted and the top byte shifting into the bottom byte, assigning 0x00ED into u16r.

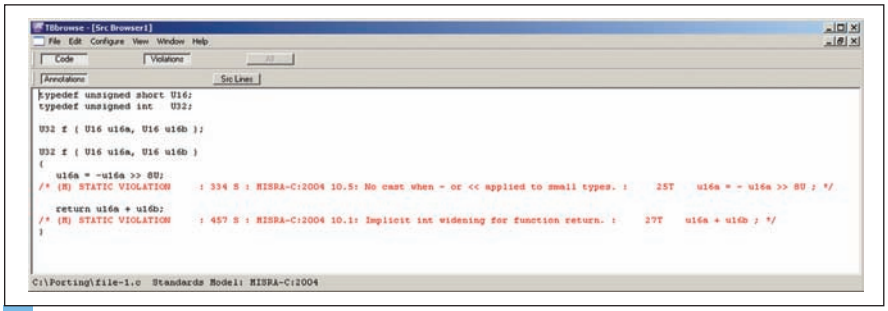
TBrowse - [Src Browser1]
File Edit Configure View Window Help
Code
Violations
Annotations
Src Lines
typedef unsigned short U16;
typedef unsigned int U32;
U32 f (U16 u16a, U16 u16b);
U32 f (U16 u16a, U16 u16b)
{
u16a = ~u16a >> 8U;
/* (M) STATIC VIOLATION : 334 S : MISRA-C:2004 10.5: No cast when ~ or << applied to small types. : 25T u16a = ~ u16a >> 8U ; */
return u16a + u16b;
/* (M) STATIC VIOLATION : 457 S : MISRA-C:2004 10.1: Implicit int widening for function return. : 27T u16a + u16b ; */
}
C:\Porting\file-1.c Standards Model: MISRA-C:2004

Figure 1 | Static analysis tools such as the LDRA tool suite can highlight issues within valid C code that can cause functional errors when ported. Because the code is valid C, compilers will not detect these issues.

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However, on a 32-bit architecture, u16a will be converted to signed int (with 32 bits) before the complement takes place, resulting in the value 0xFFED being assigned into u16r.

Once again, the use of a cast will ensure the behavior is as expected:

```
u16r = ( U16 )~u16a  >>  8;
```

Evaluating code suitability

Static analysis tools are an invaluable aid to code porting. As shown in Figure 2, these tools permit developers to evaluate legacy code and ensure that new code is developed in a way that allows it to be ported.

Early adoption of static analysis in a project life cycle will ensure that legacy code is validated as early as possible and that any new code is portable from the outset. Developers can rapidly recover the initial outlay involved in using such tools through reduced development time and significantly lower residual defect levels. ECD

Chris Tapp is a Field Applications Engineer at LDRA, based in the UK, where he specializes in programming standards. With more than 20 years of experience in embedded software development, he spent most of his career as a consultant in the automotive, industrial control, and information technology industries. Chris serves in the MISRA C working group and is currently chairman of the MISRA C++ working group. He graduated from the University of Durham in 1987.

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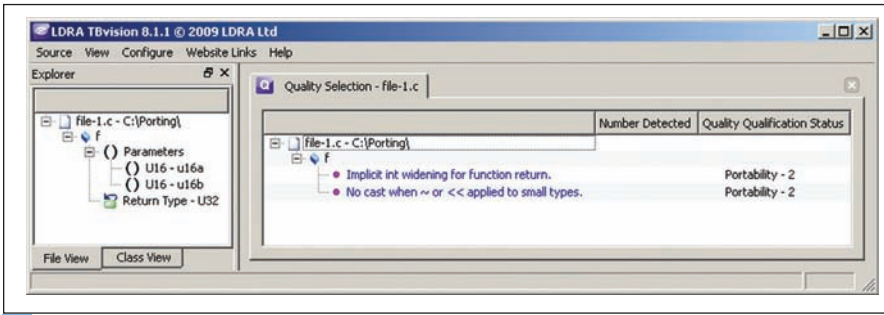

Figure 2 | Static analysis tool reporting such as this example from the LDRA tool suite enables efficient evaluation of the suitability of code for porting.

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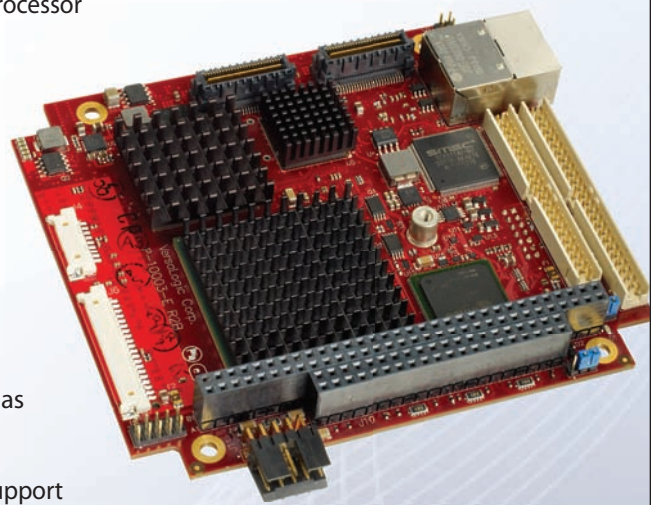

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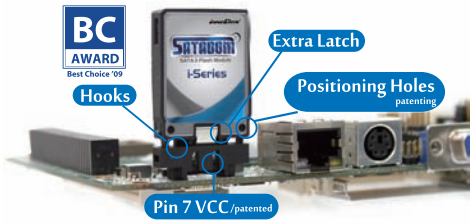

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Debugging the Android platform on ARM-based designs

By Achim Nohl

With new platforms come new debugging tools, as well as more awareness of processor architectures and platform middleware specifics. Achim presents an example of simplifying Android debug capabilities using a virtual development board.

Bringing up Android on a new device cannot be accomplished without touching the internals of the Android software stack. While the Java application layer remains to a large extent unmodified, work must be done in the Java native layer, the hardware adaptation layer, and the underlying Linux kernel and its drivers. Furthermore, device-specific services and applications need to be integrated and tested along with the rest of Android.

Vertically integrating a device feature across all those layers in the software stack is a fair challenge. Isolating and debugging one software module in a single layer can be tough; what's more, debugging multiple interacting modules across all layers is not supported by any debug framework and thus requires patience and many printf trace messages.

To solve this, CoWare developed the Virtual ARM Development Board for Android, which provides an Android-aware debug and analysis framework that enables a deterministic and successive top-down debug approach. The Android awareness is first noticeable by the ability to detect and trace ARM Linux operating system contexts such as interrupt handlers, kernel threads, drivers, and user space processes. The ability to observe process scheduling immediately renders insight into overall system behavior.

As an example, Figure 1 shows an online context trace of a system deadlock after a device resumes from a deep sleep suspend mode. While the device is waking up but not reacting on any keys or touch screen, the system is trapped in a deadlock between a software interrupt (swi) handler and Android's input device reader process (InputDeviceRead). With this analysis, it becomes obvious that no other important processes such as the window manager are served to handle a key press.

Supporting the top-down debug flow, each process can be further investigated on the function up to the instruction level. Even memory accesses are traced, which allows an effective analysis of behaviors across layers in the software stack.

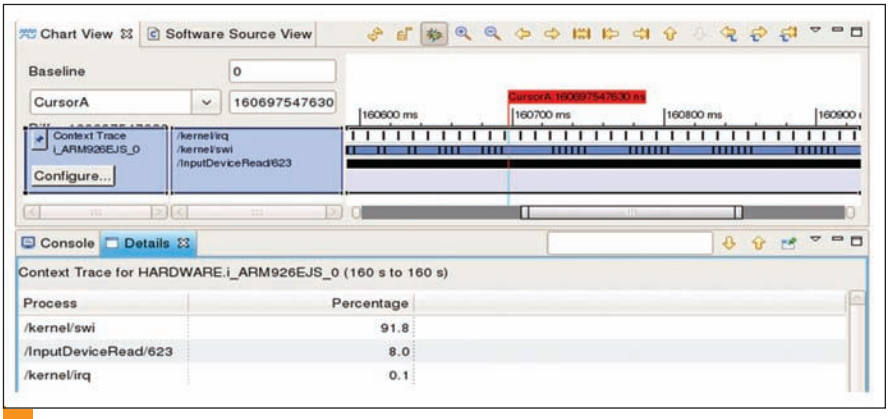

Figure 1 | An online context trace shows a system deadlock after a device wakes up from deep sleep suspend mode.

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Figure 2 illustrates the function level interaction between the Android input device reader process and the kernel software interrupt. Identifying which code actually gets executed helps isolate the locations in the large third-party software code base that require the developer's attention and demonstrates how software interacts across the various layers. In Figure 2, observe how an Android middleware function read_notify triggers the kernel software interrupt swi.

The analysis solution integrates the logging and tracing capabilities that exist in Android and Linux. Without instrumentation or changes in any parts of the software, the Android logger and kernel debug messages are captured and visualized along with the previously introduced traces. This way, developers can continue to use those facilities with the added value that all logs and traces are synchronized and can be easily correlated with the process and software function, as shown in Figure 3.

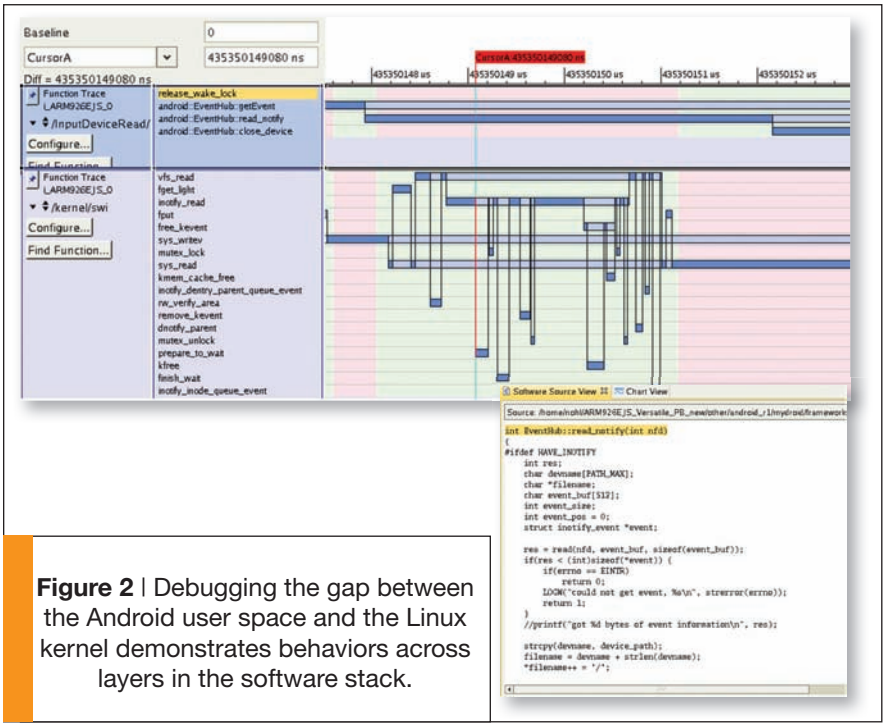


Figure 2 | Debugging the gap between the Android user space and the Linux kernel demonstrates behaviors across layers in the software stack.

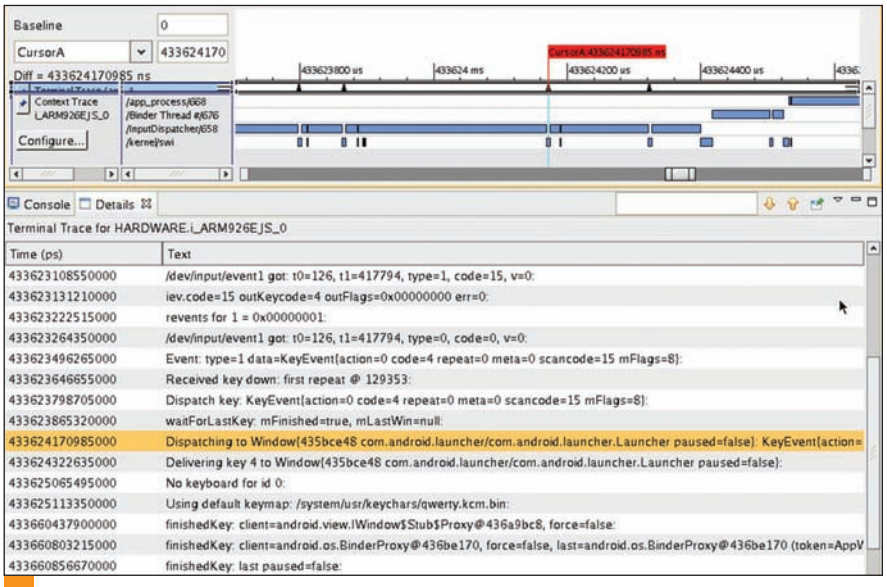
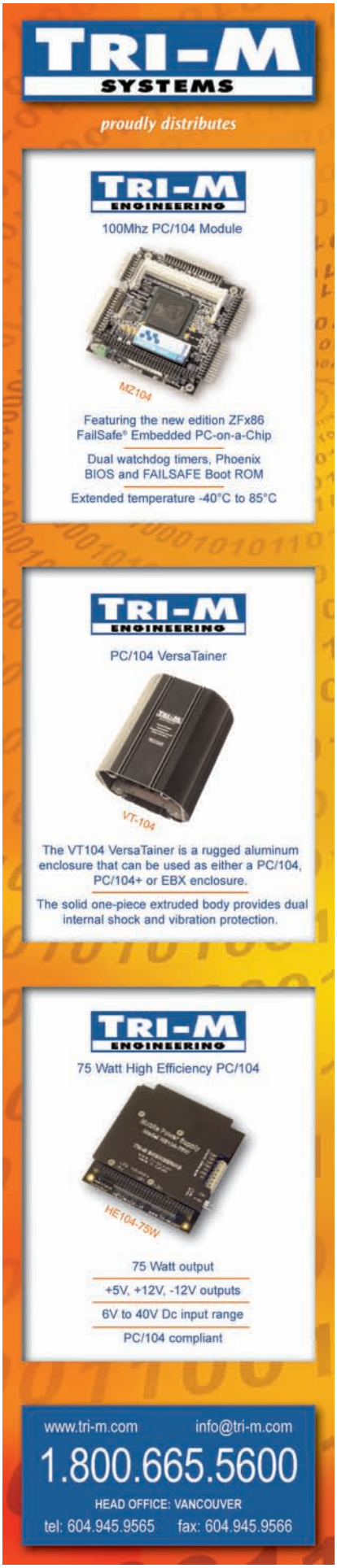

Baseline
CursorA
Diff = 433624170985 ns
Context Trace
/app_process/668
/Binder Thread #/676
/InputDispatcher/658
/kernel/swi
Configure...
Console
Details
Terminal Trace for HARDWARE.i_ARM926EJS_0
Time (ps)
Text
433623108550000 /dev/input/event1 got: t0=126, t1=417794, type=1, code=15, v=0:
433623131210000 iev.code=15 outKeycode=4 outFlags=0x00000000 err=0:
433623222515000 revents for 1 = 0x00000001:
433623264350000 /dev/input/event1 got: t0=126, t1=417794, type=0, code=0, v=0:
433623496265000 Event: type=1 data=KeyEvent{action=0 code=4 repeat=0 meta=0 scancode=15 mFlags=8}:
433623646655000 Received key down: first repeat @ 129353:
433623798705000 Dispatch key: KeyEvent{action=0 code=4 repeat=0 meta=0 scancode=15 mFlags=8}:
433623865320000 waitForLastKey: mFinished=true, mLastWin=null:
433624170985000 Dispatching to Window{435bce48 com.android.launcher/com.android.launcher.Launcher paused=false}: KeyEvent{action=
433624322635000 Delivering key 4 to Window{435bce48 com.android.launcher/com.android.launcher.Launcher paused=false}:
433625065495000 No keyboard for id 0:
433625113350000 Using default keymap: /system/usr/keychars/qwerty.kcm.bin:
433660437900000 finishedKey: client=android.view.IWindow$Stub$Proxy@436a9bc8, force=false:
433660803215000 finishedKey: client=android.os.BinderProxy@436be170, force=false, last=android.os.BinderProxy@436be170 (token=AppV
433660856670000 finishedKey: last paused=false:

Figure 3 | Developers can visualize Android logger and kernel debug messages along with previously introduced traces.



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Notice that the Android log is not separated from the important kernel debug messages, and viewing those messages no longer requires working user space applications (such as dmesg or logcat). Traces often need to be accessible when the system is corrupted and the viewer applications or debug bridges are not operating anymore. An example is the early phase of the boot or the transition to and from deep sleep mode. This analysis solution captures the traces directly from the embedded software through the nonintrusive control and inspection capabilities that a virtual platform provides.

The Virtual ARM Development Board and tools complement the existing development environment for Android with powerful system-level analysis tools. The board works with tools such as the Google Eclipse SDK using the Android Debug Bridge. State-of-the-art debuggers such as RealView Debugger (RVD), Lauterbach, or Data Display Debugger (DDD) can carry out embedded software debugging using the board as a target instead of hardware (see Figure 4).

This high level of visibility and the nonintrusive inspection and controllability makes debugging Android a much more streamlined and predictable task. ECD

Achim Nohl *is a principal solution specialist for virtual platform and processor design solutions at CoWare, based in San Jose, California. As one of the main inventors of LISATek technology, he led the research and development of the CoWare Processor Designer product line until 2006. In the past two years, he has taken over the technical lead for the definition of virtual platform-based software development solutions. Achim holds a degree in Electrical Engineering from the Institute for Integrated Signal Processing Systems in Aachen, Germany.*

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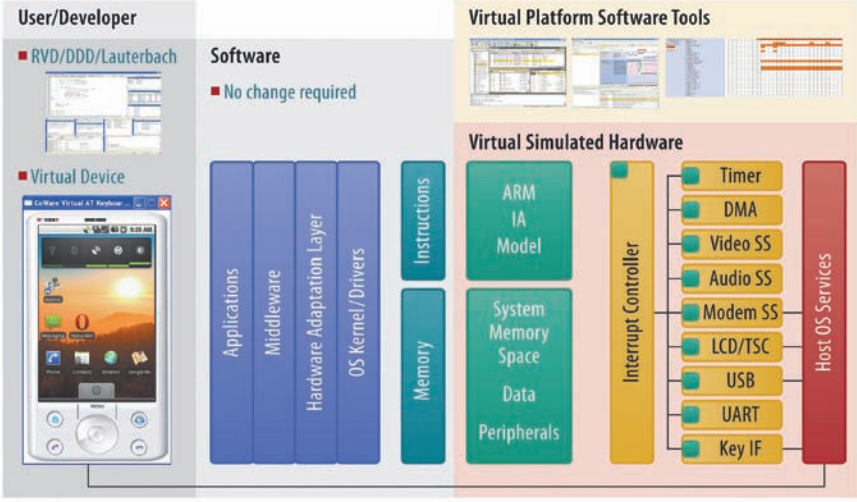

Figure 4 | The Virtual ARM Development Board complements a range of powerful analysis tools and debuggers.

Quick Guide

See page 22 for more info on reading the 2D barcodes.

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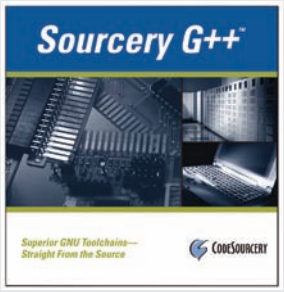
Sourcery G++ Development Tools



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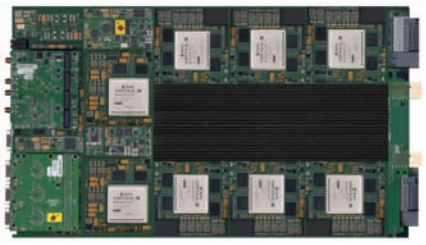

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Editor's Choice

Video at lower cost for more apps

The idea of a media application processor supporting video decoding and 2D acceleration isn't news, but a price point of $11.40 in 10K for those features is. Atmel has introduced the SAM9M10 based on a 400 MHz ARM926EJ core.

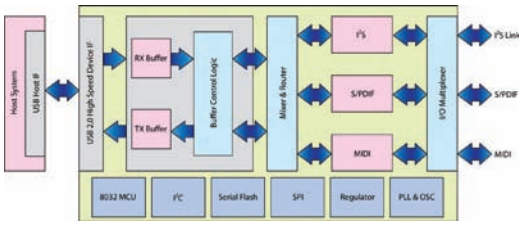
At the high end of Atmel's ARM9 families, the SAM9M10 decodes video streams up to D1 (720 x 576 pixels) or WVGA (800 x 480) at 30 frames per second (fps). It also has USB 2.0, Ethernet, MMC and SDIO interfaces, an LCD controller, and CMOS camera and audio interfaces. One interesting twist is integrated support for 1.8 or 3.3 V supply voltages. The part is fully supported with Linux and Windows Embedded CE board support packages.

Atmel | www.atmel.com | **RSC#** 44126

Finally, USB 2.0 audio

This is one of those head-scratchers for me. Why, when there is USB 2.0 in almost every system, are there not USB 2.0-enabled chipsets to handle some obvious functions like audio, especially high-quality audio? VIA Technologies now offers what the company claims is the first USB 2.0 audio controller.

The VIA Envy VT1730 is an 8-channel, 24-bit/192 kHz audio controller made for systems with a USB 2.0 connection. Supporting multiple audio streams at full bandwidth and quality opens up new applications such as audio hubs, recording consoles, and Musical Instrument Digital Interface (MIDI) devices that need a lot of data streamed quickly. The VT1730 also supports I2S for Blu-ray Disc audio content protection.



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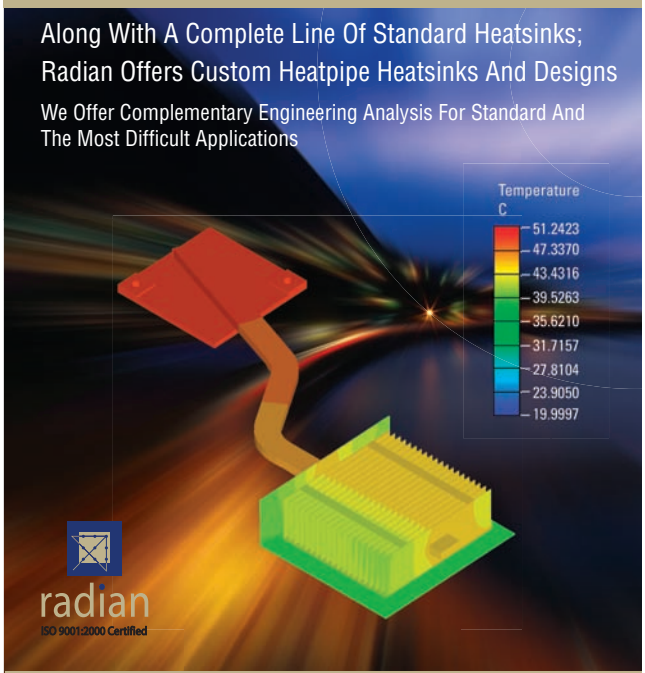

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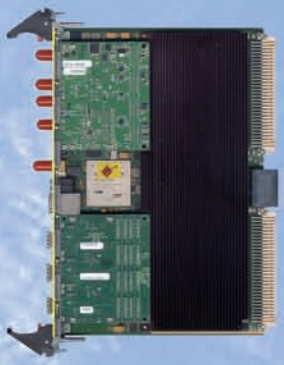

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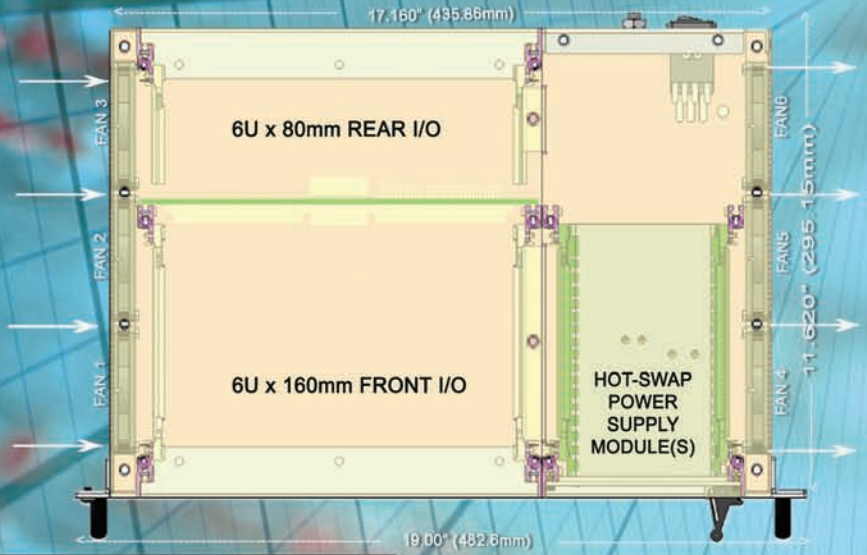

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